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Data Reduction Procedures for Laser Velocimeter Measurements in Turbomachinery Rotors

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DATA REDUCTION PROCEDURES FOR LASER VELOCIMETER MEASUREMENTS IN TURBOMACHINERY ROTORS

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INTRODUCTION

Blade-to-blade velocity distributions based on laser velocimeter data acquired in compressor or fan rotors are increasingly used as benchmark data for the verification and calibration of turbomachinery computational fluid dynamics (CFD) codes. Using laser Doppler velocimeter (LDV) data for this purpose, however, must be done cautiously. Aside from the still not fully resolved issue of the seed particle response in complex flowfields, there is an important inherent difference between CFD predictions and LDV blade-to-blade velocity distributions. CFD codes calculate velocity fields for an idealized rotor passage. LDV data, on the other hand, stem from the actual geometry of all blade channels in a rotor. The geometry often varies from channel to channel as a result of manufacturing tolerances, assembly tolerances, and incurred operational damage or changes in the rotor individual blades.

In high speed fans at certain operating conditions, the rotors exhibit noticeable differences among the velocity fields of individual rotor blade channels.

Figure 1 serves as an example. The figure, which presents an extreme case of a high speed fan rotor operating at off-design conditions, shows axial velocity distributions in each of the 44 rotor blade channels (notice that the velocity was measured in 43 out of 44 channels). The differences in axial velocity profiles among individual blade channels are striking.

Understandably, in a situation like that in Figure 1, the question which immediately arises is which blade channel is the "right" one to use for CFD code verification; or alternately, should the channel velocity profiles instead be first averaged over the rotor and then the resulting average channel distribution used. A follow-up question is how faithfully the resulting average velocity profile represents the "correct" velocity distribution for the given operating conditions. In essence, the question is how much "agreement" or "disagreement" is required or should be tolerated in comparison with the CFD predictions to approve a particular CFD code as a reliable tool for a given task.

To responsibly approach the questions raised above, it must be understood how the laser velocimeter (LV)

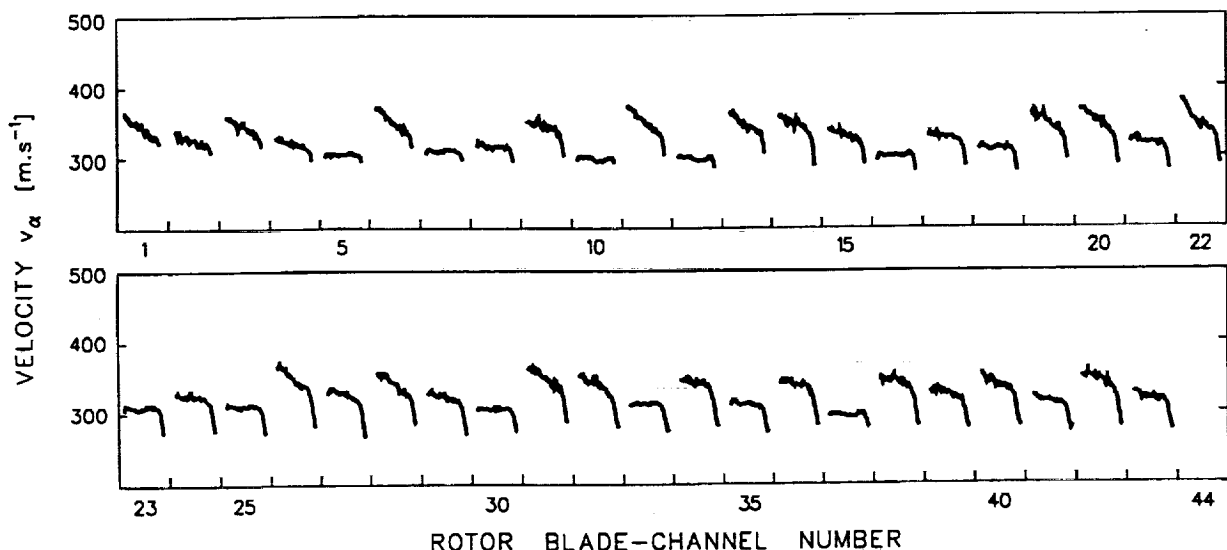


Figure 1. Axial velocity distribution for off-design operation in a high speed fan rotor.

results were generated. A common approach to acquiring periodic data is to employ conditional sampling and ensemble averaging procedures. Ensemble averaging of LV data acquired in a spinning rotor can be done in several ways. In the early days the LV system was "turned on" only for a selected angular position of a rotor to record velocity values at that particular location in the rotor. With the advent of accurate rotary encoders, much more efficient data acquisition was possible. An LV system "works continuously", and a recorded and validated LV velocity sample is immediately tagged with a particular angular position generated by the rotary encoder. Currently, the two basic approaches are either blade-channel conditional sampling or rotor conditional sampling. In the blade-channel sampling procedure, the rotary encoder is restarted at the beginning of every blade passage. Consequently, *each LV data sample* has the same "weight" in the procedure that generates the resulting blade-channel velocity profile. In the rotor sampling approach, the rotary encoder is restarted by each rotor revolution. In this approach *each blade channel velocity distribution* "weighs" equally during the averaging over the entire rotor when the resulting blade-channel velocity profile is generated. It is the goal of this paper to describe and discuss the data reduction procedure used by the author for LV data acquired recently in the rotor of a high speed fan.

THE NATURE OF LV MEASUREMENTS IN SPINNING ROTORS

A specific feature of laser velocimeter measurements made in spinning rotors is that the "probe traversing" in the circumferential direction is provided by the rotation of the rotor. As depicted in Figure 2, in the relative frame of a spinning rotor, the LV probe first moves from the center of the first blade (point C_1) to cross the first blade suction surface (point S_1), then passes by the blade channel centerline (point C_0) to cross the pressure surface of the second blade (point P_2), and finally moves by the center of the second blade (point C_2) to repeat the same sequence for the following blade channel. The circumferential traversing of the LV probe is therefore determined by the rotor rotation; as a result, the instantaneous pitchwise position of the LV probe can be predicted. On the other hand, an LV velocity data sample is acquired only when a seed particle crosses the LV probe and its signal is validated by the LV circuitry, which unfortunately, cannot be predicted. As a consequence, LV velocity data are acquired randomly. Care must be exercised to correctly locate the randomly measured flow velocity samples with respect to a moving blade channel.

A typical LV data set contains a very large number of velocity samples (80 000 to 100 000 for the case of the presented data). The flow velocity samples, acquired in a random sequence during a time interval of several

thousands of rotor revolutions, were rearranged by the post-processing procedure based on one of the ensemble averaging methods and are presented as a velocity distribution along the blade-channel pitch. Figure 3 is an example of such a velocity distribution. The distribution follows the time sequence along the LV probe trace line indicated in Figure 2. The depicted velocity profile is not a result of only one blade-channel crossing. The profile shown here as a continuous curve actually consists of discrete LV velocity samples acquired randomly along the rotor circumference. To generate the resulting velocity profile, the radial, axial, and instantaneous circumferential LV probe positions must be known with sufficient accuracy [Lepicovsky (1993)].

Many equally important conditions must be met to successfully conduct LV measurements in a fan or a compressor stage. Two of these conditions are the existence of the LV probe (measurement volume) and its visibility. Both the existence of the LV probe and its visibility are affected by obstacles in the optical path (e.g., rotor blades). The obstacles for the transmitting optics determine the probe's existence; the obstacles in

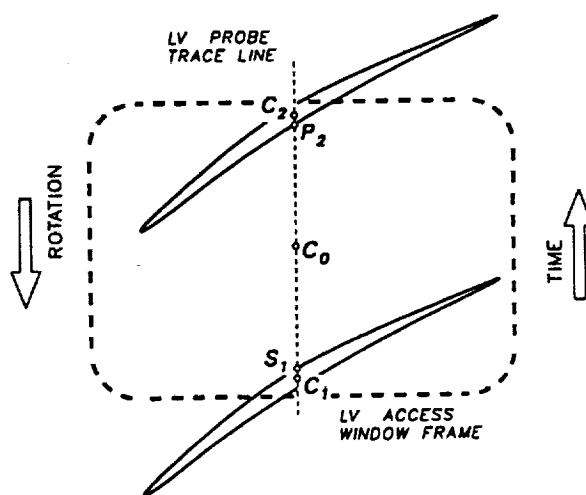


Figure 2. LV probe trace line.

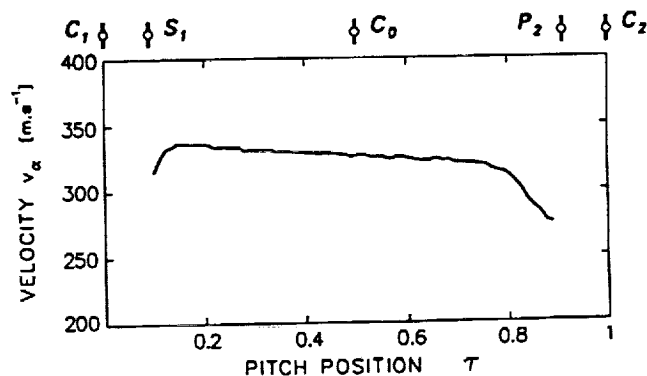


Figure 3. Blade-to-blade axial velocity distribution.

the path of the receiving optics determine the probe visibility [Lepicovsky (1993)]. Full probe visibility implies that there is no interference between the light-collecting cone of the receiving optics and either the fan casing or the rotor-blade geometry. In a blade tip region, these two conditions are satisfied provided there is a suitable access window in the fan casing. Deeper in the blade channel, however, the blade geometry may significantly restrict the region where the LV probe exists or is visible (optical shading).

The ranges of visibility and existence for the LV probe must be determined to distinguish between regions where the LV signal could originate only from the seed particles and those regions where the LV signal could also be generated from the LV probe interference with blade surfaces [Lepicovsky (1993)]. Occasionally, such signals may satisfy the validation criteria of an LV processor and they can be accepted as valid velocity data. Of course, if an LV processor validates any signal which did not originate from the visibility region, that signal must be rejected from the procedure that generates flow velocity profiles.

THE RANDOMNESS OF THE LV DATA

To illustrate the random nature of LDV signals, Figure 4 depicts a time interval of one revolution of a high speed fan rotor. A time scale at the bottom of the figure indicates the time elapsed from the beginning of the particular revolution. Utilizing the same data set already shown in Figure 1, the figure shows a time sequence of recorded LV data samples taken during the 61st revolution of the fan rotor after the onset of the LV data acquisition process. To record a sufficient number of LV velocity samples for the entire data set, the LV

data were recorded over an interval of 48.4 s, which was equal to 10 414 rotor revolutions. The total number of recorded LV samples was 94 164, thus giving an average LV data rate of 1.95 kHz. As seen in Figure 4, however, there were 30 LV data samples recorded during this particular revolution, which translates to a momentary LV data rate of 6.5 kHz. Even though the LV data rate during the 61st revolution was more than three times higher than the average data rate, it was not high enough for us to be able to record at least one velocity sample in each blade channel of the fan rotor (44 blades). Consequently, a data reduction procedure must properly reconstruct the blade-to-blade velocity distributions from a very sparsely populated data sequence. In order to place the random LV samples at correct pitch positions in a particular rotor blade channel, the LV signal is tagged with the instantaneous angular position of the rotor. For the case under discussion, the angular resolution of the tagging electronics was 0.1 dg, thus giving 82 positions per one rotor blade channel pitch. The LV data recorded for rotor blade channels 6 through 11 during the 61st revolution are shown in Figure 5 (circular markers) together with the velocity distributions generated later from all the LV data acquired for the given fan operating conditions (as already shown in Figure 1). Again, the time scale in this figure shows the time elapsed from the beginning of this particular revolution of the fan rotor.

CONDITIONAL SAMPLING

In order to construct the velocity distribution in a spinning rotor, the LV data must be acquired using a conditional sampling technique. Conditional sampling of LV data, described in detail by Strazisar & Powell (1981)

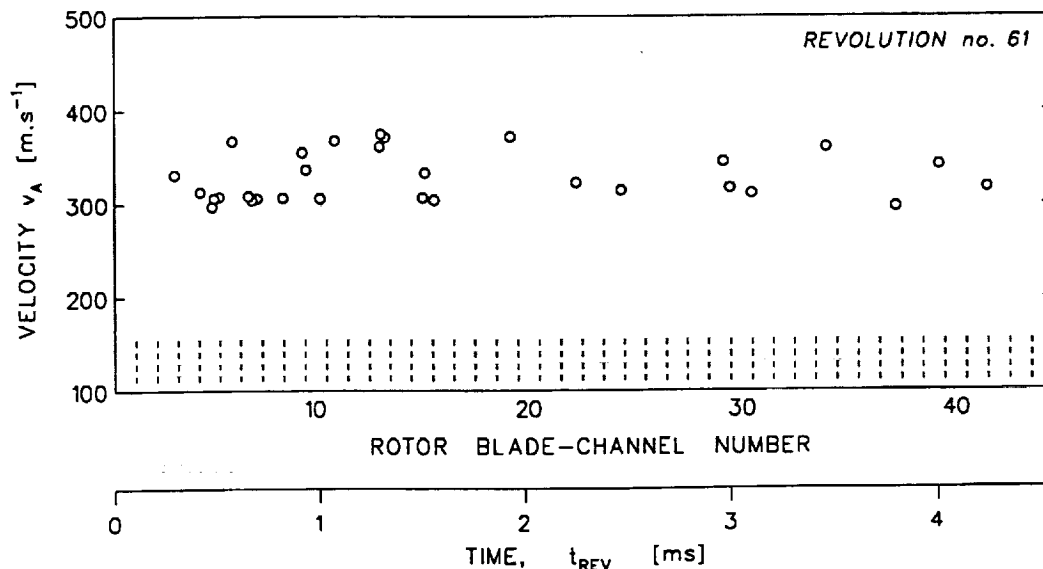


Figure 4. Sequence of LV samples recorded for one revolution of the fan rotor.

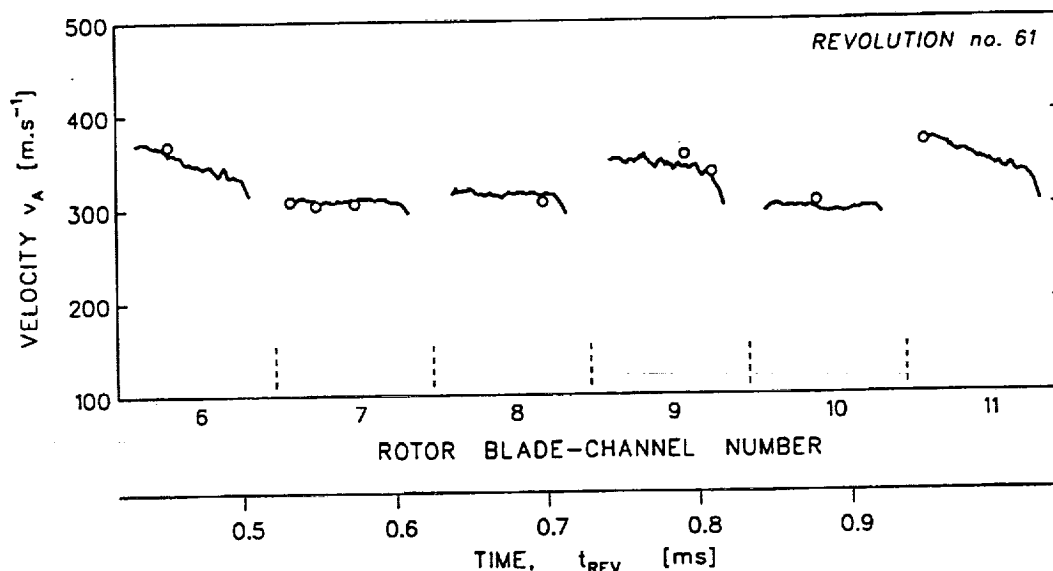


Figure 5. Sequence of LV samples recorded during one passage of six rotor blade channels.

and Lepicovsky & Bell (1984), can be triggered either by a blade passage (channel sampling) or by a rotor revolution (rotor sampling). Using true blade-channel sampling, each blade when passing by the LV probe repeatedly initiates a time sequence of the LV data acquisition. In this way, all LV data recorded in different blade channels are "piled up" into a single file representing an average blade channel width. Consequently, blade-channel sampling results in a blade-to-blade averaged velocity distribution over an average single blade channel (Figure 3). In contrast, for rotor sampling, the sequence of recorded LV data is repeatedly initiated by each rotor revolution and the LV data are "piled up" into a single file representing the entire circumference of the rotor (Figure 1). Thus, rotor sampling results in an averaged velocity distribution over the entire circumference of the rotor. A pseudo blade-channel sampling method utilizes LV data acquired in the rotor sampling mode; however, the sequence of recorded LV data is divided into segments equal to one blade-channel pitch flyby interval and then the LV data are "piled up" into a single file equal to the width of a rotor blade channel.

Each of the sampling methods has its advantages and problems. For example, to construct a blade-to-blade velocity distribution using the blade-channel sampling; only a moderate number of LV samples needs to be acquired. Therefore, this approach can be used to advantage for the cases of limited memory capacity of the data acquisition electronics, cases of low LV data rates, or cases when the total time of data acquisition is restricted by the operating conditions of a tested hardware. However, the need to repeatedly initiate the data acquisition sequence by each blade passage restricts this method to cases with a low blade passing frequency e.g., Lepicovsky & Bell (1984). The rotor sampling approach, on the other hand, requires large memory

capacity for the data collection device and a high LV data rate. The major advantage of this approach is that the data allow inspection of changes of the velocity patterns from channel to channel. This approach, however, requires a large number of LV samples to be collected, which means longer data acquisition times and a large memory capacity. The pseudo blade-channel sampling approach tries to utilize advantages of both previously discussed methods. The drawback of this method is the decreasing accuracy of LV data placement at correct pitch positions with an increasing time interval from the instant of the once-per-revolution (OPR) triggering signal which repeatedly restarts the rotary encoder. The OPR signal also controls encoder's "speed". Consequently, the encoder is locked to the previous revolution time and "does not know" the immediate rotor speed, which may slightly vary. Larger velocity variations are flagged by the end-of-revolution encoder count, and the LV data for such revolution will be discarded. However, for velocity variations within the encoder limits even small deviations from the correct pitch positions may strongly affect the velocity and velocity unsteadiness values, especially in regions of high velocity gradients in the vicinity of blade surfaces. The data discussed in this paper were acquired using the rotor sampling mode. The results, shown here, were generated using either the rotor sampling or pseudo blade-channel sampling approaches. The term blade-channel sampling in the following sections actually refers to the pseudo blade-channel sampling method.

CLEANING PROCEDURES FOR LV TURBOMACHINERY DATA

Spurious and statistically insignificant data entries should be removed from an LV data set at the onset of the data reduction procedure. Three data "cleaning"

schemes were employed in our approach: (1) histogram clipping, (2) ensemble clipping, and (3) visibility clipping.

Histogram Clipping

The first cleaning procedure, called histogram clipping, is based on a population cut-off limit of a velocity histogram generated from all acquired LV samples disregarding the time sequence (instantaneous angular position) of their acquisition. It is a common approach in non-periodic flows outside turbomachinery measurements to use velocity histograms for judging the quality of the collected LV data [Petrie *et al* (1988)]. For turbomachinery data, such an approach is usually not adopted [Strazisar *et al* (1989)] because the value of the overall data velocity histograms for interpreting rotor or blade velocity distributions is questionable. In non-periodic flows with constant mean velocity, the velocity histograms are used to estimate the mean velocity value and the root-mean-square (RMS) value of velocity deviations from the mean (σ) of the flow in question. After that, all velocity samples which deviate more than $\pm 3\sigma$ from the mean are discarded for their statistical insignificance. In turbomachinery rotor flows, however, the value of local mean velocity is not constant but depends on the particular pitch position inside the blade channel. For the rotor flows measured in the non-rotating frame, the local mean velocity is a strong function of time; it is periodic with the blade passing frequency. The variability of the mean velocity of rotor flows is the reason why the overall velocity histograms cannot be used in the same manner as is common in non-periodic flows. Still, the velocity histogram plays an important role in the procedure for cleaning LV data from rotor flows. The overall data histogram can be used to eliminate LV data with low statistical significance based on the *velocity bin population* value rather than on the deviation from the mean.

The overall data velocity histogram, generated for a velocity resolution of 1 m.s^{-1} , is shown in Figure 6. To enhance the visibility of the sparsely populated velocity bins, the histogram is replotted in Figure 7 utilizing a logarithmic scale on the ordinate. The population cut-off limit for data cleaning was selected to be 1% of the population of the most populated velocity bin. The limit was 21 in this particular case. The cut-off limit can be set independently or it can be related to some fraction of the most populated velocity bin. For pure Gaussian distributions, the population cut-off limit and the RMS value are mathematically related. For skewed histograms of turbomachinery rotor flows, the relation between the population cut-off limit and RMS values is not straightforward. The author's experience is that the population cut-off limit should not be less than 10 velocity samples per bin.

Ensemble Clipping

The cleaning procedure to follow the histogram clipping is applied either to the channel or rotor data sets, depending on which type of sampling was employed. For channel sampling data sets, all of the acquired LV samples were allocated to particular pitch positions in a single blade channel (Figure 8). After that, the data subsets at each of the recorded pitch positions (82 in the described case) were treated separately. Since the data were acquired in the sampling mode synchronized with the blade passing frequency, the time dependence of the velocity signals with respect to the rotor motion was removed and the individual velocity data sets at each pitch position can be treated as having constant mean velocities. Velocity histograms for each data subset were generated and the mean values and the root-mean-square

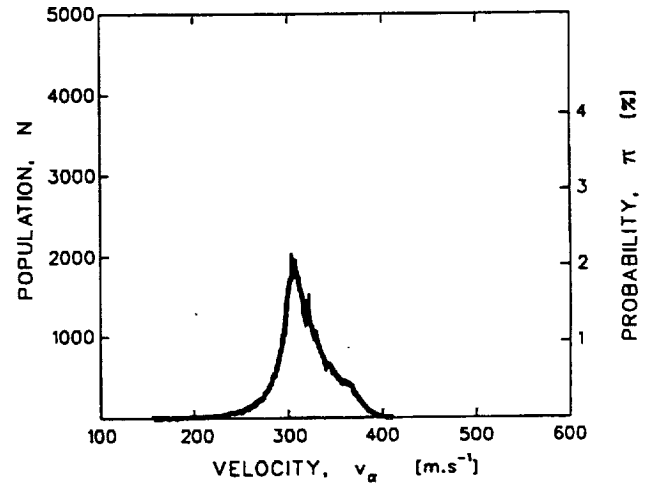


Figure 6. Over-all data velocity histogram of recorded LV samples.

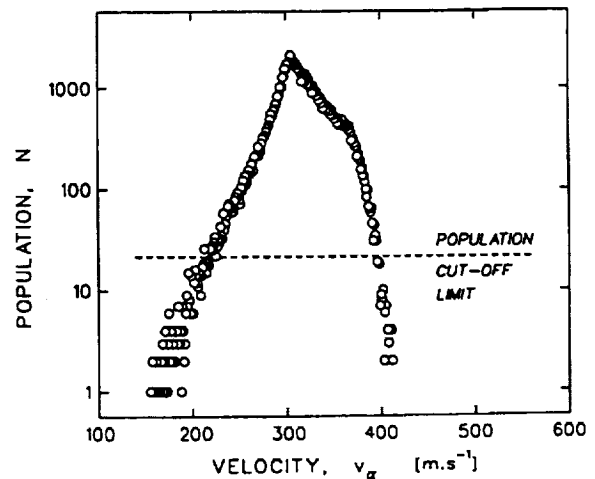


Figure 7. Population cut-off limit of a velocity histogram.

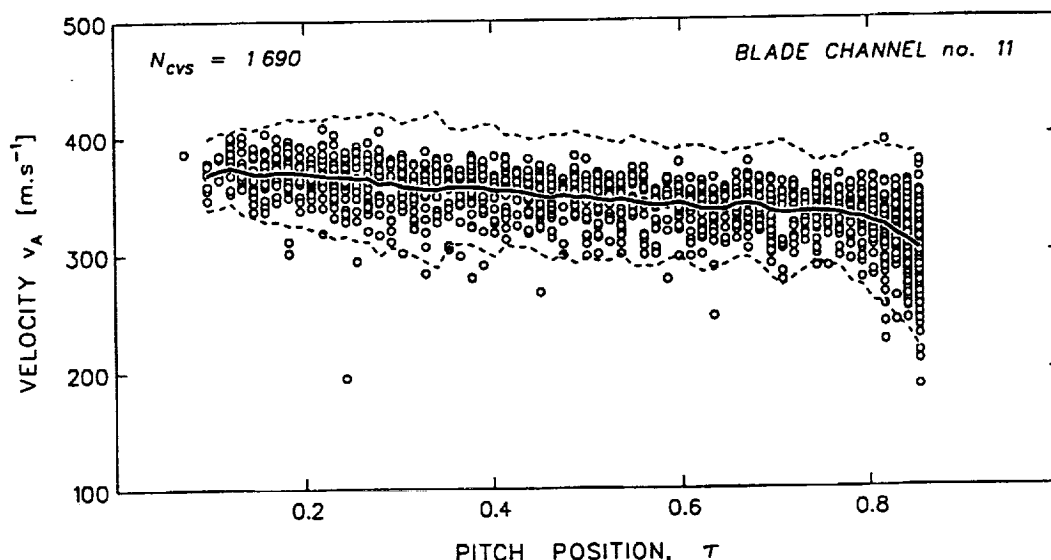


Figure 8. LV samples recorded in a channel sampling mode.

standard deviations (RMS) were calculated for each of the data subsets. The resulting mean velocity values along the blade-channel pitch are shown in Figure 8 by a solid line; the dotted lines show the $\pm 3\sigma$ (standard deviations) of individual data subsets at each of the 82 pitch positions. Then, all the velocity samples outside of the $\pm 3\sigma$ band were rejected for their low statistical significance, and both mean and RMS values were calculated again for the remaining velocity samples. Next, a population cut-off threshold was set for the blade-channel data ensemble for the entire blade-channel. Again, the cut-off threshold can be set arbitrarily or it can be related to the most populated subset at any of the pitch positions. Usually, the cut-off threshold is equal either to 1% of the population of the most populated data subset or to a minimum of 10 velocity samples, whichever is greater. All data subsets with populations less than the selected threshold were eliminated because of their low statistical significance.

The procedure of ensemble clipping for rotor sampling data sets is similar to the previous procedure for channel clipping; however, in this case, it is repeated separately for each blade channel in the rotor. The individual rotor blade channels have a lower data population than was the case of the single blade channel for the channel sampling; therefore, the population cut-off threshold is lower than in the case of blade-channel sampling. For the current data, the cut-off limit for the rotor sampling procedure was set to 5 velocity samples. Elimination of some of the data subsets at some of the pitch positions for rotor clipping could lead to gaps in the velocity distribution for some of the blade channels, which is a trade-off with data reliability. The resulting data file represents the velocity distribution for the entire rotor for an average revolution of the rotor (Figure 1).

Visibility Clipping

Visibility clipping is the last cleaning procedure applied to the LV data. Its purpose is to eliminate LV samples which could possibly originate from the LV probe and blade surface interaction (blade flash). It is based on mapping the rotor blade channel in terms of LV probe visibility. By masking the LV data with a visibility map, the LV samples at pitch positions close to blade surfaces, which could originate from the blade surface reflections, are eliminated. The visibility clipping procedure is performed in the data post processing. Visibility clipping is discussed in detail by Lepicovsky (1993) and is mentioned here only for the sake of completeness.

THE BLADE-CHANNEL VERSUS ROTOR SAMPLING APPROACH

The cleaned LV data consist of individual data subsets for each position along a blade-channel pitch or the rotor circumference. The individual data subsets contain information about the velocity distribution (mean values) as well as the velocity unsteadiness distribution (standard deviation values). The velocity information can be used for comparison with the CFD predictions. The data generated by the channel sampling can be used directly since they depict velocity or velocity unsteadiness distributions over a single rotor blade channel (Figure 9). The data generated using the rotor sampling (Figure 1), however, must first be averaged over the entire rotor. The resulting single channel distributions are shown in Figure 10. The vertical bars at pitch positions of $\tau = 0.2, 0.4, 0.6$, and 0.8 indicate the range of average axial velocity values in individual rotor blade channels as reported in Figure 1. As can be seen by comparing the

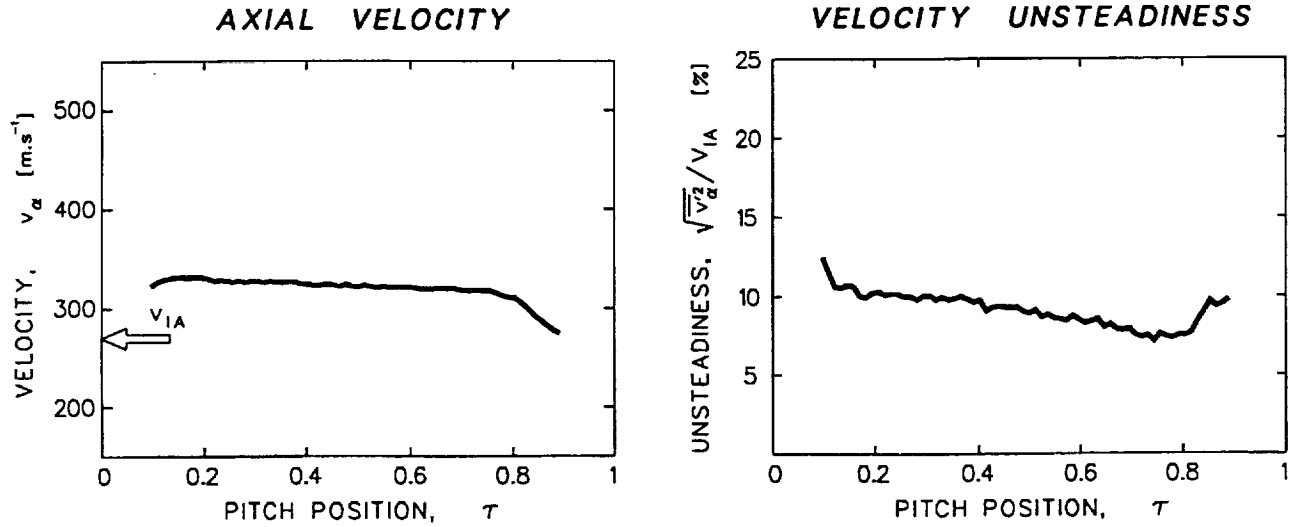


Figure 9. Velocity and velocity unsteadiness distributions generated using the blade-channel sampling mode.

leifthand sides of Figures 9 and 10, there is practically no difference between both velocity distributions, and it appears they can be used interchangeably. This conclusion seems to be true even for large channel-to-channel differences for cases of data sets with sufficiently high populations of LV samples. In our case the above conclusion was valid for measurements with at least 25 LV samples per pitch location and blade channel (rotor sampling). Even though there are no visible differences in velocity distributions for the blade-channel and rotor sampling approaches, rotor sampling should be preferred because it allows inspection of channel-to-channel differences (Figure 1). However, for cases of low data rates and a small number of acquired samples with very uniform rotor flowfields, blade-channel sampling can be safely used.

Contrary to the velocity case, there are noticeable

differences for distributions of velocity unsteadiness generated by these two methods. The velocity unsteadiness levels generated by the blade-channel sampling method are visibly higher (righthand side of Figure 9) than those resulting from the rotor sampling method (righthand side of Figure 10). Clearly, the rotor sampling procedure followed by averaging over the entire rotor removes the channel-to-channel deterministic and periodic fluctuations from the resulting velocity unsteadiness distribution. Consequently, the resulting velocity unsteadiness distribution contains only random velocity fluctuations, which approximate flow turbulence intensity [Lepicovsky (1986)]. In most cases, however, the resulting unsteadiness levels are still slightly higher than the flow turbulence true levels because of the contaminations resulting from the nonuniformity of seed particle sizes and the effects of uncertainty in determining

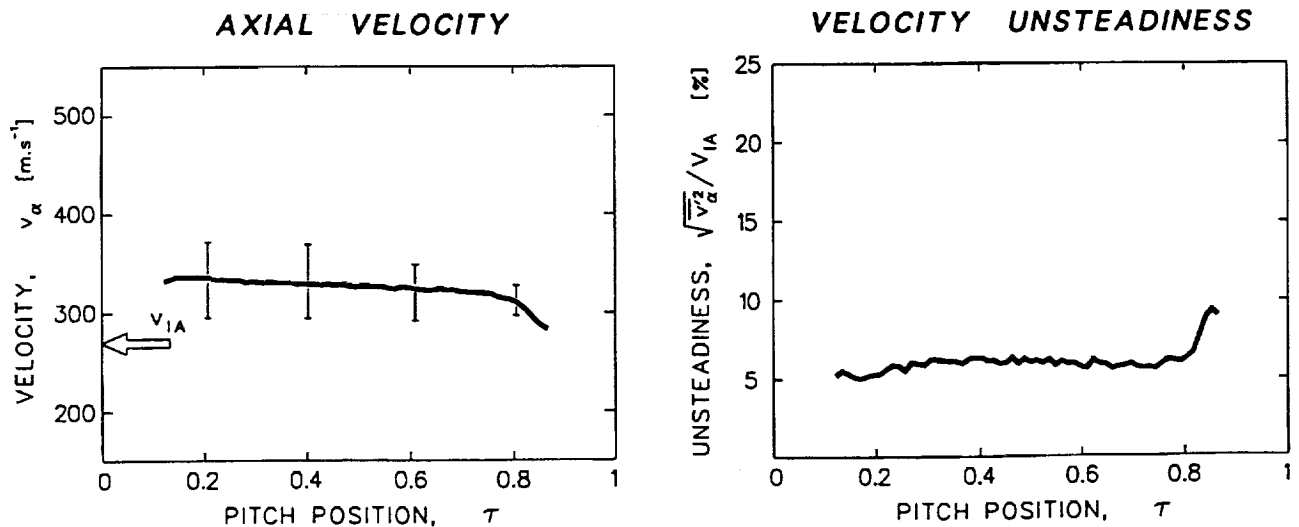


Figure 10. Velocity and velocity unsteadiness distributions generated using the rotor sampling mode.

the pitch position (especially in the regions of high velocity gradients). In any case, the average velocity unsteadiness for the rotor sampling (as shown in the righthand side of Figure 10) is a measure of velocity fluctuations in the rotating system (inside the spinning rotor), while the velocity unsteadiness distribution for the channel sampling (the righthand side of Figure 9) is a measure of velocity fluctuations felt on nonrotating elements in the flow path behind the rotor. The velocity unsteadiness, shown in Figure 9, determines the maximum amplitude of the excitation force for flow-induced vibrations on nonmoving structural components.

A strong argument in favor of the rotor sampling approach is the ability to capture the flowfield over the entire rotor, as shown in Figure 1. The range of velocity differences among individual rotor channels generated using rotor sampling is summarized in Figure 11. The velocity profile in the upper left corner shows the resulting average blade-to-blade velocity distributions. The subplot in the upper right corner shows velocity profiles from all rotor channels simply "piled-up" on each other. The remaining two subplots show five "low" and five "high" rotor channels plotted separately (but not averaged). The high and low channels were determined based on the value of average velocity in each individual blade channel. The figure demonstrates that for the particular fan operating conditions, the velocity level difference among individual rotor blade passages reached up to 80 m.s^{-1} , which is 25 % of the average mid-channel axial velocity, and that the velocity distribution for "low" channels exhibited a different trend across the blade channel than the velocity distribution for the "high" channels. Channel-to-channel velocity variations were observed for most of the fan operating regimes

investigated; in a majority of cases, the variations were substantially smaller than that depicted in Figure 1. In any case, however, the variation pattern was always the same; it is that the same blade channels were always either "high" or "low" regardless of the operating conditions. The repeatability of the nonuniformity pattern indicates that the velocity channel-to-channel variations were connected to the differences in the geometry of individual blade channels.

CONCLUSIONS

The acquired LV data shed new light on the flow physics of high-speed fan rotors. The recorded channel-to-channel velocity variations are important information which must be taken into consideration when using the experimental data to evaluate the accuracy of CFD codes. The information about channel-to-channel variations cannot be derived from the CFD methods since it stems from the actual rotor geometry, while the CFD predictions are based on an idealized rotor passage.

The ability of rotor sampling to capture the channel-to-channel velocity variations is an important factor in favor of the rotor sampling approach. It is the author's view that rotor sampling should be preferred even though it is more demanding on a high LV data rate and a large memory capacity of the data acquisition electronics. The total number of acquired LV samples must be sufficiently high to secure enough velocity data per pitch position in each rotor channel for the resulting data to be statistically significant.

Finally, there is no universal answer to what data reduction procedure should be used for data comparison

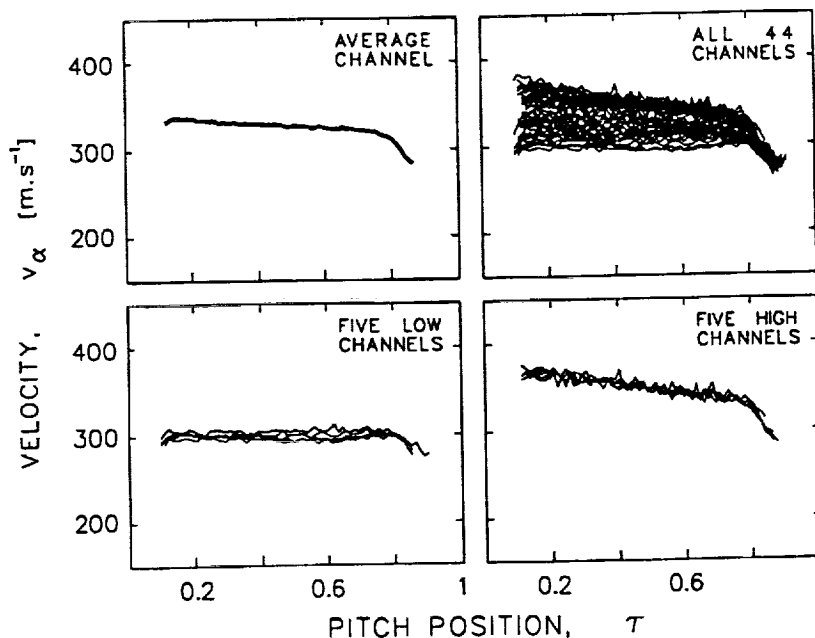


Figure 11. Channel-to-channel velocity variations.

with the CFD predictions. It should be judged case by case. Obviously, for flow conditions as depicted in Figure 11, it makes little sense to spend excessive effort trying to adjust the CFD predictions to every detail of the experimental data. Rather, the comparison should focus on trends in the velocity flowfield development and on comparison with global flowfield characteristics.

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